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# Innovation logics in the digital era: a systemic review of the emerging digital innovation regime

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# Innovation logics in the digital era: a systemic review of the emerging digital innovation regime

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**ABSTRACT**

This essay reviews the ontological status of digital material in industrial operations and conditions it provides for innovation. It recognises the semiotic quality of digital material and the critical role of von Neumann architecture as to show that digital innovation advances through a three pronged, largely orthogonal process of embedding- a process of interlacing elements of one innovation domain to that of another. Three types of embedding define digital innovation: operational embedding (code-computer), virtual embedding (real-world phenomena-code) and contextual embedding (performing code-social setting). Each constitutes a 'leverage point' for further expanding digital innovation and they interact dynamically while industrial innovation is defined by a static virtual and contextual embedding. The processes that underlie innovation in the two regimes follow differential logics. In industrial regime (1) discover-synthesise and (2) manufacture-distribute activities combine to form the leverage points for innovation. In digital regime 1) discover product or behaviour (ideation); 2) abstract to digital material (virtualise); 3) Implement and replicate digital material (variations in operational/contextual embedding); and 4) Deliver product and/or behaviour (perform digital material) activities form the leverage points for innovation enabling wider, open, and faster innovation with a distinct value logic.

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## Introduction

When writing this essay in the late spring and summer of 2020, multiple icons of the 20th-century retail industry – J.C. Penney, J Crew, and Neiman Marcus, the early stalwarts of its business model – filed for bankruptcy, followed by 200-year-old Brooks Brothers. The pandemic of 2020 was the last straw for these companies and made them join the earlier failings of Sears, Kmart, and many others. At the same time, the 'born digital' Amazon.com has become one of the most valuable companies globally and an invincible competitor. Importantly, the failures of these companies cannot be attributed to the lack of trying and innovating as they have been doing it for decades. Nor can the failings be attributed to poor management because it is highly unlikely that all these companies were poorly led and could not hire top managerial talent. Rather, it appears to be a story of a systemic failure that led the companies to innovate in wrong places, at

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wrong time, and in a wrong way. Essentially, the companies could not ultimately innovate how they should innovate as dictated by the emerging digital innovation regime.

The challenge for innovation scholars has been how to frame, understand, and explain the new context of innovation brought about by pervasive digitalisation. The context now permeates all industries and their business models. It is novel in that it cannot be explained by older models that allowed many companies of industrial era to succeed for a century or so. The new context raises a host of so far unanswered questions, such as: Why does the established, industrial model of innovation invented during the era of mass manufacturing and distribution – including the concept of retail department stores – and perfected under the auspices of industrial organisation not work anymore?[1] How and why does the logic of innovation differ, and is it hard to learn and assimilate for incumbents despite their significant advantages in competencies, skills, resources, and market visibility? What brings the change so fast and results in such a widespread devastation? Difficulty in answering these questions raises doubts about the plausibility of received ideas and explanations of industrial innovation brought forward during the past century. For example, these explanations cover Chandlerian concepts of how strategy begets structure and are driven by scale and scope, Porterian ideas of positioning and value extraction or resource-based explanations of the merits of unique and stable resource constellations. These assume in one form or other on static notions of industry and its change and how these are driven by scale and scope effects. Most of the well-tried ideas to account for innovation in such settings such as product versus administrative innovation and radical innovation versus incremental innovation, have clearly lost much of their magic or work only in limited ways.

This raises the question of what explains innovation and makes it successful in an era of pervasive digitalisation? Are there truly novel systemic ways of engaging and managing in innovation, which we can call digital innovation regime and are distinct in kind from that of the previous industrial innovation regime? Much research produced over the past decade to explain ‘digital’ has offered fresh and reasoned insights into why and how the digital calls for a new vernacular of innovation. In particular, major advances have been made to characterise the ‘new’ in digital innovation including:

(1) What the novel features of the digital innovation are such as its layered and loosely coupled nature (Lee & Berente, 2012; Tilson et al., 2010), its inverse use and value logics (Baskerville et al., 2020), or how the digital transforms the scope and features of physical products and their innovation (Baskerville et al., 2020; Sandberg et al., 2020);
(2) What the ontology of the digital material is and why its properties propel new forms of innovation (Baskerville et al., 2020; Faulkner & Runde, 2013; Kallinikos et al., 2013; Tilson et al., 2010; Yoo et al., 2010). These have been commonly attributed to combinability, reflexivity, programmability, nearly zero variable cost features of digital material, and so on;
(3) What the features of the digital innovation environment are (Nambisan et al., 2017) and how they affect innovation processes (Lyytinen et al., 2017; Nambisan et al., 2017; Yoo et al., 2012);
(4) Why features 1–3 result in powerful tendencies towards network effects, platformization, and generativity as key organising principles for business (Alaimo et al.,

2020; Constantinides et al., 2018; Karhu et al., 2018; Parker et al., 2016; De Reuver et al., 2017).

The primary focus of these works is to identify and compare differences between the old and the new regimes from a specific angle. These works have shed new and brighter light on what is different in digital innovation, such as its outcomes (fixed versus malleable), material (digital versus analogue/physical), processes (close/disciplined versus open/chaotic), organising principles (hierarchy versus platform), or economic logic (decreasing versus increasing marginal returns). At the same time, these analyses do not connect such changes to a deeper systemic change, which underlies and builds up the emerging digital innovation regime. To carry out such systemic analysis calls for a historic, comparative, relational analysis of how the previous industrial regime in essential, systemic ways differs from the emerging digital innovation regime. This a similar call that historians of industrial organisation, such as Chandler (1990) or Hughes (1989), faced when they asked this regime differs from that of craft-based production. To put it differently, we need to probe in a more abstract and systemic way the key elements that inspire innovation during industrial or digital innovation regimes based on how the elements became organised in separate, unique families of relationships and related practices consequential for enabling or constraining innovation. Thereby features, activities, and outcomes as identified in the recent studies become plausible, while the dominant ones fading away can be shown to become obsolete, infeasible, and thereby excluded by natural selection. Such form of analysis, which we so far lack, would heed to systemic assemblages of elements that underlie innovation activity and make it feasible to organise innovation in specific ways. This invites us to examine how the assemblages become phased into a specific order of relationships where specific elements are connected or disconnected, enabling alternative forms of action and thinking and related novelty (DeLanda, 2006). Based on such analysis, we can better understand why the regimes differ substantially, and there is a systemic break between industrial and digital (innovation) regimes. Such separation of 'how things work' also explains the grand challenges of why established companies have found it so hard to move from one regime to another.

To carry out a systemic analysis of this sort, I focus on what defines and distinguishes the leverage points and related phases of innovation in industrial and digital (innovation) regimes. I identify spaces where critical elements that enable or constrain innovation interact as leverage points and define them as critical resource configurations (material and immaterial) that enable and constrain where and how innovations can proceed and under which goals. This leads me to locate and identify where and how innovations are likely to take place in the regimes and the logics of how such innovations get formed and justified and under what conditions they can proceed and succeed. I offer examples of such leverage points in both regimes and illustrate that because of these differences, digital innovation unfolds as a cumulative force that cuts across industries, settings, and environments as an unstoppable gale of destruction. Generally, the analysis illustrates how industrial versus digital product properties, processes, and technologies differently shape the spaces in which innovations can unfold. I hope to narrate why the digital regime essentially differs from industrial regime in its assemblage of phases and leverage points.

The reminder of the article is organised as follows. I review critical elements and their connections (leverage points) in two innovation regimes – industrial regime and digital regime – as assemblages and discuss how the components of each regime are dynamically constituted by their relations to other parts (DeLanda, 2006). I show that each regime is consequently defined by distinct goals and constraints and different logics that call for distinct capabilities to innovate (cognitive, organisational). I show how the industrial regime has evolved through separate periods and how digitalisation has expanded in the industrial environment to sow the seeds for the emerging digital innovation regime. I show how each phase inherits features and constraints from the previous phase while opening new challenges and capabilities for innovation.

## Industrial innovation regime

### *Classic industrial innovation regime*

The industrial innovation regime was established in the context of the emergence of industrial organisation over a roughly 100-year period between 1850 and 1970. It had its heyday between 1950 and 1970. The regime is founded on ideas of stable (new) products assigned to separate markets and market segments. Product innovation mirrors and takes place in the context of visible markets or anticipated new markets. The regime's innovation and organising logic are well narrated in Chandler's detailed discussion of the evolution of corporate strategies (Chandler, 1977, 1990). Firms had to learn how to address scale and scope challenges of producing to mass markets and manage, control, and coordinate related activities to manage demand and supply variations effectively (Hughes, 1989).

The credo for innovation – introducing novelty in the regime – is how to create new product categories. This happens primarily through scientific discovery or using scientific principles to address needs in product markets and industries (e.g. car, telephone, telefax, and record player). These products serve the well-defined needs of identified customers. Derivative and complementary innovations will combine and follow the sales and use of such products and address challenges in scaling the production, quality control, and distribution- or managing-related costs, risks, and benefits. Innovation takes place sequentially (internally) through a pipe of processes that create/design new products, scale them up (continuously) for mass markets, and allocate investments to most profitable and potential market categories to serve latent/identified needs. Classic examples of companies that did well in this innovation regime are DuPont, GE, and Daimler.

The innovation regime operates through two separate and tightly connected phases. The first one focuses in creating scope economies for learning expressed in (1) discovery-synthesise activities necessary for product innovation. The phase uses discovered properties of physical matter and competencies in shaping them to serve identified and latent needs (combustion engine for transportation, radio signals for transmitting sounds, etc.). The next phase focuses on scale economies of learning expressed in (2) manufacture-distributed activities, which create and move the products to customer markets and offer complementary services for how to use them (such as service and gas stations). This phase relies on pertinent material, engineering, and social system properties and related infrastructures (such as communication and transportation systems, standards, and regulations) that cater to identifying customer needs and balancing supply and demand in the short and the long run. Overall, the regime assumes, needs, and sustains activity systems associated with both phases and seeks to establish leverage how they can jointly promote or sustain innovation. Activities in phase 1 use outputs of activities in phase 2 to acquire resources to continue innovating and gain information about the markets for new products. Activities in phase 2 need input from activities in phase 1 to continue to grow and penetrate new markets and continue to satisfy identified, growing, or segregated customer needs in established markets.[2]

A critical assumption undergirding innovation in an industrial regime is the concept of a distinct, discrete product circulating in the market system. Erecting and building know-how to bundle and operate activity systems for discovery-synthesis and manufacture-distributed phases create significant barriers to entry in terms of knowledge, capital, and access to markets (market share). This erects boundaries between activity systems related to different products and promotes the idea of distinct industries with well-defined learning scope. In each such industrial innovation domain, the innovation by character can be more or less radical. The more radical it is, the more latent the customer need, and the more exotic the new market. Consequently, products are innovated through smaller or bigger change deltas so as to balance the product innovation risks. One reason for this is that the necessary scale economies kick in only if the innovator can make the innovation to diffuse to a large enough market to recoup the initial investment and necessary scaling costs. For many years, there has been a significant interest in Rogersian type diffusion of innovation models, because they help explain conditions for successful innovation diffusion (Rogers, 2005). Generally, the innovations around manufacturing and distribution are as critical (such as the idea of a large retail store) as those related to products as such. These innovations address administrative/process changes and activity configurations in the manufacture-distributed phase necessary to balance and coordinate demand-supply challenges in industrial regime (manufacturing, distribution and operations) (see Hughes, 1989, for detailed history).

Essentially, the regime's leverage points for innovation are continued expansion of new (mass market) products through discovery of properties of the matter that allow them to fulfil new latent customer needs. Initial discovery is followed by constant product improvement and increased small variation, calling for competencies in industrial design and market segmentation, and continued innovations in manufacturing, distribution, and customer services to administer costs. Not surprisingly, digital technologies were initially mobilised as critical elements for administrative innovation starting in the 1950s (Yates, 1989). They create unprecedented efficiencies and speed to scale operations and later offered support for scope economies (such as better integrated product development and related knowledge management) (Yoo et al., 2010). The industrial regime model dominated innovation until the early 1980s when the notion of product platforms emerged in multiple industries (cars, computers, consumer electronics, etc.). This change was associated with the global reach of the industries, which posed new challenges in product development, manufacturing, and distribution because of increased variation in local product needs and the need to use manufacturing and distribution resources efficiently across the globe. This triggered the second phase of industrial innovation regime, called modular industrial innovation regime.

### *Modular industrial innovation regime*

This innovation regime extends the industrial innovation regime. Instead of focusing on product categories as individual innovations, it introduces variability, flexibility, and speed in responding to emerging customer needs and technological change. It permits more efficient use of global manufacturing and distribution chains and related capacities. The regime expands the notion of a product innovation towards higher abstracted class of product platforms and the concept of product variability (Gawer, 2009, 2014). Platform-based innovation needs to be enabled by new administrative innovations centred on abstracted design rules and capabilities that would leverage those rules. The design rules specify specific standardised interface principles and rules that guide decomposing the products into functional components where the relationships between the components are defined by design rules dictating generalised functional relationships between module interfaces (Schilling, 2000). Use of such rules affords looser coupling between product components and products: one to many instead of one to one (Baldwin & Clark, 2000). Their use allows significant variation in products as product components and subsystems treated modules can be varied in several places of the product hierarchy. Moreover, these hierarchies can be extended without a need to synthesise a totally new product for each design. Modularity enables more efficient use of the manufacturing and distribution capabilities in scale and scope because products and components are now loosely connected during the manufacture-distributed phase.

Consequently, an extended logic underlies product innovation in modular industrial innovation regime. It now consists of three phases: (1) discover-synthesise; (2) modularise-combine; and (3) manufacture-distribute. The innovation centred on modularise-combine phase distributes the product innovation and manufacturing innovation across the modules of the product architecture as soon as the *synthesise-combine* innovation around the platform architecture had been carried out. The abstracted platform solution enabled by the synthesise-combine phase creates more flexible and responsive supply chain ecosystems with lower cost and higher product variability. It also allows inventing new combinations of modules as separate products of new categories (e.g. mobile phone versus game console) creating higher flexibility to respond to new markets when new product categories emerge.

Leverage points in this state are largely the same as in the previous regime. Discover-synthesise still dominates, while modularise-combine introduces variation and flexibility to create faster new products with lower cost. Platform-based product variations open wider innovation spaces in the supply chain and afford economies of scale and scope and how to balance trade-offs therein.

One benefit in the modular industrial regime is that innovation can be distributed down and externalised to modules when the platform architecture has been fixed (Lee & Berente, 2012). The regime emphasises the critical role of product orchestrators as enablers and governors of product ecosystems. Truly new product categories emerge rarely, while variations in products and modules are more frequent because they offer stepwise means to advance product features and variability across technology generations when better technologies become available for key components. Examples that deploy such opportunities are generations of mobile phones, computers, or cars. Iconic companies that leveraged effectively modular strategy are Volkswagen/Audi, Toyota, Nokia, and Airbus. This later form of industrial innovation regime would not have been possible without innovations in inter-organisational digital capabilities that allowed sharing standardised product descriptions using CAD/CAM systems (Argyres, 1999; Yoo et al., 2010) and exchange of standardised trading messages (e.g. Electronic Data Interchange (EDI) and product identification standards). These allowed more efficient, faster, and more scalable coordination within the design and supply chains to manage design, manufacturing, and distribution activities (Malone et al., 1987; Yoo et al., 2010).

## Digital innovation regime

### *Nature of digital material*

Until the early 2000s, digital technologies supported mainly design, administration, and coordination activities across two or three phases of the industrial innovation regime. Digital technologies carried out narrow functions in specific product components, such as controlling oxygen and gas levels in a carburettor (Lee & Berente, 2012).[3] During the 1990s and early 2000s, because of exponential growth in internet use and capabilities (Hanseth & Lyytinen, 2010; Tilson et al., 2010) digital technologies turned into infrastructural functions and capabilities and became everyday objects and experience. This growth expanded digital capabilities and their use beyond organisational boundaries to industries, regions, and societies. The technologies could now combine in accessible forms extensive storage and computation functions with connectivity to varied digitised data, enabling large-scale use (Lyytinen & Yoo, 2002a). This has resulted in the two decades that followed a structural shift and reorganisation of the innovation regime to digital innovation regime. While earlier industrial regime components and capacities have remained, their use has become increasingly realigned with digital capabilities. At the same time, new capacities have been invented, creating a new kind of assemblage where the old and new components have been realigned. As a result, the material conditions and logics for innovation now fundamentally differ. The infrastructural nature of the digital material (in that it is accessible at any place, time, device, and to any user) fundamentally differs from that of physical infrastructure. The underlying economics and problems of scale, scope, and supply-demand coordination change accordingly. To understand how this shift has been possible, I briefly discuss the differentiating features of digital material. Thereafter, I review how the digital material has now become deeply embedded or connected to a wide range of socio-technical relationships of most organised activity, offering radically different and novel leverage points for innovation.

Digital material has been extensively theorised since about 2010 (see Kallinikos et al., 2013; Tilson et al., 2010; Yoo et al., 2010) for its properties, such as reprogrammability (Yoo et al., 2010), its use features including nonrivalry (Faulkner & Runde, 2019), and its generative nature (Henfridsson & Bygstad, 2013; Lyytinen et al., 2017; Tilson et al., 2010; Yoo et al., 2010; Zittrain, 2006). I build on these reviews with two specific goals in mind. First, many properties suggested in the past overlap, and we still lack a coherent and parsimonious set of properties that articulate what distinguishes digital material and its operations from physical matter. It is also essential that identified properties are separate from each other and from their higher-level effects (such as generativity). Second, most analyses ignore that digital material comes in two forms, which are necessary and complementary for any use: software (code) and data. Consequently, one should state which properties apply to which type of digital material, that is, which ones are common to both data and code and which ones apply to only one. I identify four properties of digital that characterise all digital material. I also observe one property that applies to software (code) only. These five properties offer a minimal foundation for articulating the effects of the properties of digital material that are essential for building up digital innovation regime.

All digital material is semiotic in nature in that it consist of strings of 0's and 1's drawn from an alphabet of digital binaries to form digital representations.[4] The property of using bit strings allows exactness in expressing any digital object and makes such objects addressable, that is, each can be retrieved based on their unique signature of 0's and 1's (Yoo, 2010). A universal alphabet leads to homogenisation in that all digital materials, no matter what they ultimately stand for – be it code, sensor data, audio, text, video – are subject to the same representation scheme (Yoo et al., 2010). The semiotic and convention-based nature of representation opens up an abstract and unbounded space for expression. Anything can be expressed and dressed in digital material as long as the rules, conventions, and operations have been established whereby the strings of 0 and 1 are connected with one another and their counterparts outside the digital object. Digital objects are not restricted by the limitations of the physical world; they are virtual outcomes of mutual agreements of what each digital object stands for.

Von Neumann architecture offers a physical principle and generic solution to manipulate and compute over digital objects. Use of von Neumann architecture adds two important properties to digital material. First is the possibility to realise and store bits in an electronic format. Electrification (and its ephemeral nature), in contrast to using physical wiring-based computational solutions, makes digital material editable and therefore fluid and ephemeral. Editability enables easy and low-cost modification (Kallinikos et al., 2013), making digital objects malleable in ways not possible for physical products (Yoo, 2010). Second, digital material is executable and performative in contrast to conceiving the computation as just a mathematical representation of a Turing machine abstraction. Due to electrification, bit strings stand for executable operations on real machines that manipulate manifestations of digital objects fast and with low cost. Commonly, the code guiding such processes is referred to as software. It is important to understand full symmetry, which any programmer who has programmed in machine code knows: software is also digital material and can be easily edited or made to refer to other data (code). This makes software executable but also brittle.[5] Furthermore, the semiotic quality of code – the separation of code from physical realisation (performance) – makes software reprogrammable. It allows creating an infinite variety of software functions and related performances that are only constrained by the imagination and skills of the code originators (Yoo et al., 2010). The expansive and executable properties have led to an increased performative role of code in business settings due to its 'its apparent ability to "make things happen"' (Mackenzie & Vurdubakis, 2011, p. 6).

### *Modular layered architecture and embedding*

Digital material is inherently modular. This helps express the code's functionality at the interfaces and hide how the functionality is implemented (Baldwin & Clark, 2000; Parnas, 1972). Yet these interfaces are semantic agreements of what the bit strings expressing the interface mean. In consequence, digital objects can be connected to multiple types of topological arrangements as long as the semantics of the connections at the interfaces have been sorted out. Because of performativity of material, the modularisation can be realised in run time, as currently implemented in cloud solutions and web services. However, modularity 'runs much wider and deeper in digital material' (Kallinikos et al., 2013, p. 360). It is not constrained by physical features but dictated by the semantics either in the form of code functions or data being represented and transferred at the interface. By using gateways, there is also the possibility of creating bridges between incompatible interfaces (Hanseth & Lyytinen, 2010). Combinations of modularity and reprogrammability and use of gateways produce excess recombinability of digital material (Faulkner & Runde, 2013). For example, software modules can be freely reused (due to nonrivalry), and they do not suffer from wear and tear. They can be connected through a large variety of interfaces or replaced with other modules. The same applies to data as long as there is a way to combine meaningfully data to larger chunks operated by the code (Kallinikos et al., 2013). This allows digital material to be organised in multiple alternative ways across several modular hierarchies, which each manifests specific functions or needs (Lyytinen, Yoo, & Boland, 2016; Yoo et al., 2010). This property of digital material undergirds the concept of loose coupling available in digital product architectures. Loose coupling guides organising code functions and computing resources into multiple abstraction layers connected through shared interfaces, called modular layered architecture (Tilson et al., 2010; Yoo et al., 2010) (Figure 1).

In the modular layered architecture (Figure 1), distinct functions and data are organised into separate, loosely coupled layers that jointly create a service stack, offering a digitally enabled service. This is the idea of the loosely coupled stack of N-layers expressed in the middle of Figure 1. This generic product architecture underlies now most products that share extensive digital components, from smartphones to cars and automation systems (Lyytinen et al., 2016; Sandberg et al., 2020; Yoo et al., 2010). The architecture follows von Neumann architecture in that the lowest layer represents the 'executing' (though replaceable) hardware that computes, stores, and plumbs the data. The second layer represents the abstracted digital material as a semiotic entity – the executable code (the stored programme) and data. The material can be organised further into specific functions that deal with separate elements composing the computing task as is normally done in organising the code: content layer (data/storage of data and code) and service layer (computable code for users with a business function), connected through an abstracted networking capacity (connectivity between devices). These functions are shown in Figure 1 by the N digital layers. At the top, the computing process sits an interpretation of what the computing is functionally/organisationally about, that is, what the bit strings represent in terms of real-world actors, assets, exchanges, or services (such as a ride share) in a

To innovate in any meaningful way, the architecture orchestrates sets of activities that will tie the three layers together and make them coevolve over time. In this way, the

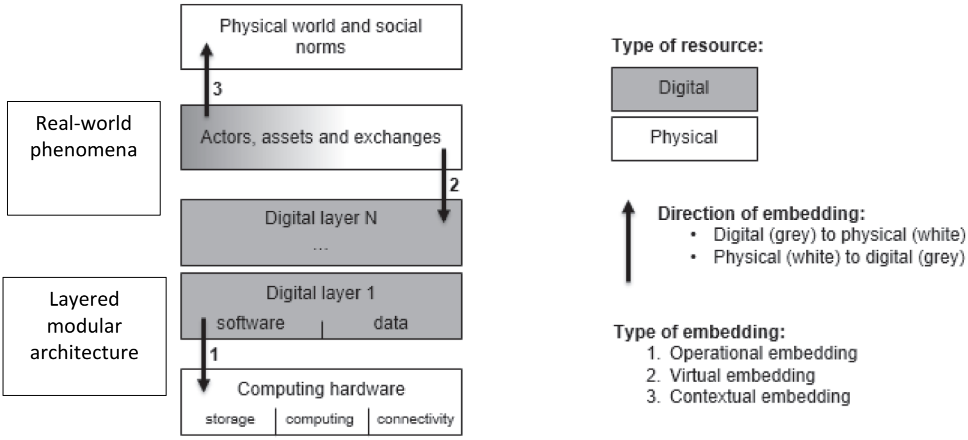


Figure 1. Modular layered architecture and digital-embedding processes use context with its guiding laws, constraints, norms, and habits.

digital and the two physical layers make the computing with the digital material tangible, reliable, and scalable and the bits being manipulated meaningful for the setting. Most of the processes that make this possible need to be worked out prior to the execution of the service stack in any setting. They form necessary conditions for any successful digital innovation, which involve the initiating element of creating an abstract digital material (to-be-performed digital twin) and connecting this material back with the physical and social worlds for novel outcomes. I posit that each process connecting the digital to the material (or between digital layers) establishes a critical leverage point for digital innovation to proceed.

The three sets of activities connecting the layers – what I call operational embedding, virtual embedding, and contextual embedding – are shown by arrows 1–3 in Figure 1.[6] They are further detailed in Table 1. They can be analytically inferred by probing the properties of the digital material and imagining their consequences for processes where digital material participates. 'Operational embedding' (arrow 1) refers to innovations that embed sets of specific digital objects with a set of hardware to be executed and operated as physical assets. In the opposite direction (upward), virtual embedding (arrow 2) refers to how real-world phenomena, such as an organisation's assets, actors, entities in physical environment, immaterial objects (money, equity), and all sorts of activities (buying), become virtualised through agreed-on representations in digital material. The goal in virtualisation is eloquently and fully expressed in the idea of a digital twin: anything that takes place or is represented in the physical/social world can have a mirror representation in the digital material (Grieves & Vickers, 2017). Finally, contextual embedding (arrow 3) refers to how the digital material, when performed, becomes contextualised into an (organisational) setting and performed in ways that give a meaning, direction and new functions (agency) to that setting (Mackenzie & Vurdubakis, 2011). This happens when

**Table 1.** Leverage points of digital innovation regime.

| Three innovation leverage points | Definition | Outcomes | Value | Constraining conditions |
|---|---|---|---|---|
| Operational embedding | The digital material coded and stored physically and run on hardware allowing sensing, recalling, connecting, computing, and display. | Operational embedding consists of sensing of digital material from input devices, storing and computing on them, and actuating the results on output device embedded in physical and social environments.<br>Digital material needs to be embedded physically and run to have performative effects.<br>Digital innovation relies on exponential scale and speed advances and cost reductions from operational embedding so that real-world phenomena can be virtualised and performed. | Exponential speed and scale<br>Efficiency (cost performance)<br>Loose coupling through virtualisation | Constraints of physics<br>Engineering challenges for hardware and software systems<br>Security |
| Virtual embedding | Process of virtualising real-world phenomena such as assets, actors, activities, locations into a shared (semiotic) digital representation so that the code can perform on representations (a.k.a. creation of a digital twin).<br>Created representations can be processed and performed only when operational embedding is present. | Virtualisation makes focal phenomena (e.g. states, actors, activities, places) representable in digital material such that the code can perform and operate on the material in a meaningful way.<br>Virtualisation advances available social, institutional, and organisational categorisations and enables integration of new types of properties into the evolving digital image of the world (e.g. by adding a new sensor).<br>Digital innovation requires expansive forms of virtual embedding in that the capture of digital material expands permits new innovation searches that enable growth of novel or more efficient services, products, and exchanges. | Utility and value<br>Expansion<br>Adaptability<br>Modularity | What can be potentially virtualised and expressed<br>Challenges in achieving agreements on representations |
| Contextual embedding | Computing contextualised into an organisational setting where the digital material performs and gives a novel meaning and function for the setting. | Involves human actors interacting with hardware in ways that has significance to the unfolding of the activity.<br>Digital material contextualised as performances in the here and now in ways that change the actor's proceeding and the setting. | Utility and hedonistic value<br>Real-world material effects<br>Efficiency and effectiveness<br>New activity | Social acceptance<br>Habits<br>Regulations<br>Institutional constraints |

a trade is carried out in an electronic stock exchange as it is performed by a high-frequency trading algorithm running on the cloud or when a mechanical engineer reads results of a crash simulation and changes the design of a car.[7]

Generally, Figure 1 depicts digital material in grey and nondigital physical/social matters in white. It expresses a bifurcated sandwich architecture that characterises the digital innovation regime. This also clarifies why it radically differs from an industrial regime. The latter operates primarily on material properties and their representations (car design → car), whereas digital representations address coordination and control problems of associated activities. In this regime, innovation consists sequences such as: material → (discovery) representation (synthesis) → material (manufacturing) → representation (product information). Presentations precede manufacturing (product designs), and representations follow manufacturing and distribution of raw materials and products (e.g. accounting, production planning, operations data). In the industrial regime, the physical (atom) forms the starting point of the regime, and the representation (bit) resides 'on top of it' in select points to render design, manufacturing, and distribution possible by addressing control and coordination problems.

In the digital innovation regime, digital material precedes the physical material. It is rendered digital by virtual embedding, which forms its outcome – a new type of digital material. This needs to be aligned with two temporally and organisationally distinct materialisation processes called operational and contextual embedding. These processes set up specific conditions and have specific effects on how digital innovation will unfold. Ultimately, the virtualised digital material results in innovative outcomes in the real world when all processes and properties are present. Consequently, all three processes must be leveraged during digital innovation. The most common way is to rely on multiple combinations of them over time. This promotes continued, fluid and expansive forms of innovation (Lyytinen et al., 2016; Nambisan et al., 2017). A typical innovation sequence in such digital innovation regime would consist of virtual (digital material) → operational (performed material) → contextual (performative effects) → virtual (new digital material) → operational (new performed material) → contextual (new performative effects) → contextual (use of the material in other context), and so on. I review each process and related activities separately.

## *Operational embedding*

From a computing perspective, digital material need to be embedded physically and made to run on concrete hardware (what Dyson, 2012 calls 'mud'). Without such embedding, the digital material represents only a mathematical idea of computation. I call this embedding operational embedding because it translates digital material to real operations on an instance of concrete physical hardware (arrow 1 in Figure 1). The abstraction between the hardware and digital material mirroring the hardware behaviours offers a design rule (and boundary) between the physical hardware and its evolution and separates it from the evolution of the digital material. The separation makes virtual embedding possible and separates digital innovation from the industrial innovation regime, which does not have such embedding. Operational embedding involves design and engineering principles to deploy some material properties in ways that run the digital material faster and more efficiently or makes it easier, more portable, more reliable, more fault tolerant, and so on. Embedding due to increases in computing speed and scale (Moore's law) enables further virtualisation (positive feedback loop) (Kurzweil, 2004). As a result, organisations continually seek to carry out growing set of their growing set of tasks by digitising related representations.

Generally, the hardware enabling operational embedding covers all elements of the computing environment. These elements change over time and therefore how the code can be run evolves to faster and less expensive embedding, changing the economies of what can be computed. The computing environment consists of auxiliary code and physical artefacts, which make the storage and representation of digital material as inputs and outputs possible, more user-friendly, and easier (Yoo et al., 2010). Operational embedding involves always a real physical system and takes place in a specific social setting. Therefore, it comes with its sociotechnical design challenges (and innovations) in that human actors need to be able to operate the computing environment by manipulating input and output devices, sensors, keyboards, and the like.

Over the past half century, engineers and computer scientists have advanced enormously in making the bit turn faster, more efficiently, and easier. This has been witnessed in exponential advances in electronics and miniaturisation expressed in Moore's law (Kurzweil, 2004). On one hand, the advances have moved computing from isolated, air-conditioned halls into pockets, skin, and eyeglasses (Lyytinen & Yoo, 2002b). On the other hand, it has enabled the use of massive server farms that compute in scale and hyper-speed in the cloud.[8] Ultimately, the exponential growth in the speed, scale, and scope of operational embedding has enabled constant innovation in where, how, and for what digital material can be used, pushing the use of digital material into a pervasive, mass scale taking place anywhere, anytime (Lyytinen & Yoo, 2002a). This has consequently promoted new forms of virtual embedding.

### *Virtual embedding*

To be useful, digital materials needs to be tied up with some outside phenomena. This entity, which the digital material stands for, can be anything in physical, social, real, or other digital material (due its semiotic quality). For example, ride-sharing services like Lyft and Uber, although being fully mediated by digital material and algorithmic processes, need to be connected at some point to real cars, driven in real settings, with real customers, transferring real money. For such a service to work, a lot of things need to be virtualised prior the service: the driver has to have a digital identity tied to a real person; a mobile phone needs to run the app representing and recording the activity and executing the service performance; the route needs to be represented digitally as GPS points; and the money needs to be transferred digitally by connecting to credit card accounts of users and bank accounts of drivers. I called the process of abstracting focal real-world phenomena to a set of sharable digital representations of virtual embeddings. This embedding involves social processes and linguistic processes (and related innovations) through which a set of focal salient real-world phenomena are mapped into digital material in the form of specifications.[9]

Virtual embedding often begins with established categories in the existing social order, such as categories of a taxi driver, his or her ID, and credit card number. To make innovation fluid and expansive, the virtual embedding must expand the agreements in digital material to new kinds of agreements and representations, such as use of GPS coordinates, rating of drivers and customers, and so on. Generally, virtualisation as part of digital innovation encompasses continued expansion, integration, combination, and redeployment of digital material-related agreements as they are increasingly perfected to create a digital mirror of the world. New types of virtual embedding arise from technical advances, such as new sensors (e.g. kinetic sensors that can result in agreements of your sleep and heartbeat patterns), new software functions (e.g. h-index in citation analyses), and innovative categories enabled by digital representations (e.g. a shared playlist). All such expansions open opportunities for innovating with digital services and products. Finally, all performances on digital material can be recorded and represented in the digital material (due to its semiotic quality). This creates perfect traces of how the material has been performed, creating another wave of opportunities to invent new categories using data mining (Alaimo et al., 2020). Recent developments in process automation and robotics, for example, use intelligent assistants that digitally emulate social and affective behaviours of human workers by showing affection and courteous behaviour, things that previously were the domain of humans. A majority of the novelty in use that accrues in the digital innovation regime originates from the increased value of using digital material in multiple ways for different purposes. This is possible because of the modularity of the material and its continued expansion and adaptation.

### *Contextual embedding*

Whenever a real-world product or service becomes mediated by digital material, the material and its performances need to be ultimately connected to some concrete setting (such as trading activity, a ride share, or an autonomous car driving on a road). This setting is where the digital material gets performed as part of a meaningful activity in the social or physical world, such as conducting a trade or an driving for a ride-share service. This is where the digital innovation meets the industrial regime and related physical/ social changes. The activity will have effects on the involved actor's proceeding and the setting (such as how the customer gets his or her ride). Performance on a circumscribed digital material in that setting – that is, where both operational and virtual embedding are present – moves in a reverse direction. The performance connects behaviourally to a concrete social and physical setting that forms and is an instance of the upper material tier of the sandwich. The move in reverse becomes the contextual embedding of the performance of the digital material.

Ultimately, the escalating performative effects of digital material in our lives are the outcome of the widening and intensifying virtualisation, which increases the number and the intensity of touchpoints where digital performances interact with and within real-world settings. In the early 2000s, the growth in such touchpoints was eloquently expressed in the 5A slogan: 'any time, any place, any service, any network, any device.'[10] Contextual embedding and its deepening and intensification offer leverage points for expanding the digital innovation regime. The growth in the touchpoints gained through continuously intensified contextual embedding offers, on one hand, new ways to virtualise further, and on the other hand, ways to increase the effects of performances by introducing new performances (due to the access to the setting where digital material is performed). The digitisation levels of settings – covering both virtualisation and operational embedding of computing resources – still vary significantly across different use contexts. These embeddings and their proceedings are path-dependent processes expressed in technology standards, regulations, cultural and institutional scripts, and habits that all regulate the use context and contextual embedding. The ways the contextual embedding takes place therefore differ significantly from one context to another. This applies even to the same digital innovation and related product and service that relies on the same virtual and operational embedding.[11] This variation can also explain the intense shake-up of the music industry when musical content and it representations were virtualised and contextualised into new settings mostly by outside innovators, such as Napster, Apple, and Spotify. They leveraged continuous innovations in the operational embedding (e.g. the internet, peer-to-peer networks, servers, MP3 players, smartphones, the cloud) and contextual embedding (a setting without a strong enforcement of existing regulations). The greater resilience of the newspapers can be explained in how the contextual embedding in this industry followed alternative routes, because of subscription models, advertisement money, and differences in experiences offered by having access to physical paper. No mapping into digital representations is perfect – it's just a momentary agreement – but there are limits as to how far virtualisations can be performed across contexts (e.g. challenges how to represent music for varying groups such as classical music listeners).

## Digital innovation regime: towards a research agenda

This essay has sought to conduct a broad systemic, comparative analysis that has tried to clarify the essential differences of where the innovations originate, the constraints on such innovation, and the primary logics for creating novelty and value in the industrial and digital innovation regimes. The analysis expands past work of the differences in the product architecture (Gawer, 2014; Yoo et al., 2010) and principles of organising (Gawer, 2014; Parker et al., 2016) to a broader comparative analysis of innovation systems. This allowed me to identify three leverage points, which make digital innovation possible: (1) operational embedding, (2) virtual embedding, and (3) contextual embedding. These embedding processes and their properties are summarised in Table 1. By perusing Table 1, we can understand why the three embedding processes form the epicentre of digitalisation. The intellectual merit of such analytical separation is that it invites us to focus on the dynamic, evolving interplay between digital, the social, and the institutional and how that interplay evolves and transforms when new virtualizations are invented and their operational materialisation evolves. The processes are highly distinct from the leverage points of the industrial innovation regime, which relied on the discovery of properties of the matter and organisational capacities to synthesise them into usable functions and forms needed for fulfiling human needs. Another critical leverage point was how to manufacture and distribute these products in ways that reached scale and scope economies.

The three separate leverage points entail that the rift of digital innovation regime from the industrial regime runs deeper than the idea of separating digitising and digital information from analogous information processing (Tilson et al., 2010). Each embedding offers a lens to understand a unique condition for furthering digital innovation, where each process extends beyond the technical concept of digitising by illuminating how digitalisation as a concrete, contextual, sociotechnical process becomes deeply transformative in separate spheres of organised activity. Each embedding connects the digital material to and with varied technical manifestations that are performed across multiple social worlds.

The three processes offer some germane insights that explain the unprecedented generativity associated with digital technologies and material (Lyytinen et al., 2017; Tilson et al., 2010) (see Table 1). First, the three processes operate independently in separate contexts and under different logics; they assume different expertise and knowledge and pursue different goals and ways of evaluating solution quality for each embedding. Second, these separations are only analytically meaningful. Each enable and is conducive for activities in other embedding. For example, the more prominently digital material presents and performs the social and the material world (i.e. the more real-world phenomena become digitised and are performed as part of the world), the more significant these embedding processes and their leverage become in shaping behaviours and bringing novelty. Likewise, the more activities are performed with the digital material, the more of the phenomena, not yet digitised but with the potential for virtualisation, need to be virtualised for furthering digital innovation. Third, as the range and diversity of digital material grows, it needs to be more contextualised. This calls for more improvements and innovations in operational and contextual embedding, creating a strong positive feedback cycle.

The research in digitising has always started by observing the critical importance of advances in operational embedding. In different forms, this ultimately drives all digital innovation (Kurzweil, 2004). Indeed, major improvements in this embedding have been necessary to advance digital innovation from its humble beginnings as electronic data processing in the 1960s to its current transformative power. Hardware is absolutely necessary to render digital material from a mathematic abstraction into meaningful social activity, and its cost needs to decrease at exponential rate to perform a growing bulk of digital material. This has been enabled by and called for improvements in understanding the physics of computing and architecting solutions that reliably compute in scale and speed (e.g. recent virtualisation to cloud). These advances have changed the overall organising of organisational computing functions, such as how to make available processing power, storage, and connectivity for organisational tasks and members. As a result, computing is now becoming a market-based utility organised in loosely coupled forms to deliver varying services using market-based mechanisms. This has created the need to innovate around new manufacturing processes to change the scale and scope of the operational embedding along the principles that characterise the industrial innovation regime. In operational embedding, the critical challenges currently related to the economics of scale and scope for varying needs for operational embedding and the increased quest for reliability and security, which are necessary for the continued expansion of operational embedding.

The analysis highlights the critical nature of virtual embedding. This forms the industrial, organisational, and social foundation of digitalisation and lays a necessary foundation for furthering digital innovation. Through this embedding, real-world phenomena become virtualised and subjected to common semantic agreements and organisational processes enabled by such agreements. This process relies on social and linguistic conventions and standard-based agreements and is therefore unbounded by physical constraints. It cuts across domains and context whenever there is a possibility to create a way to semantically connect any two elements of digital material (Kallinikos et al., 2013). Because of its creative, unbounded nature, the embedding forms the key driver in furthering digital innovation and generativity. Every novel service, product innovation, and digital feature calls for original semantic agreements, related performances, and their sharing in ways that offers value and utility. The embedding explains why new data and discovery of their connections through algorithms now lay the foundation for continued digital innovation. It explains the heightened interest in the value of data as the new oil of economy (Economist, 2020). The embedding also explains the recent growth of the platforms and their role in economic activity and organising (Gawer, 2014; De Reuver et al., 2017; Yoo, 2010). All platforms rely on virtualisation (1) to represent any salient product, object, or feature in the real world to be shared or exchanged (such as music, news, games, friends); and (2) to perform exchanges enabled by such representations and collect data of such performances for future prediction. These processes rest initially on cognitive, social inventions of sense-giving and sense-making associated with attaching alternative or expanded meanings to semiotic, digital material. The continued growth of virtual embedding and its combinatorial nature (Alaimo et al., 2020) promotes the expansion of digital innovation and forms the key leverage point for value creation and utility of the innovation. Although a fair amount of research has been conducted on contexts and processes of virtualisation such as those related social media (Alaimo et al., 2020), travel exchanges (Orlikowski & Scott, 2015), stock exchanges and trading (Mattli, 2019), or physical products (Grieves & Vickers, 2017) we lack more systematic accounts how such processes unfold and why they succeed or fail, and how they connect to and depend on activities involve operational embedding and contextual embedding of this virtualised digital material.

Contextual embedding is the most visible and obvious part of digital innovation. On one hand, the embedding resembles the adoption of innovations under the industrial innovation regime. Ultimately, some actor needs to find value in using digital material performances in some setting – such as its economic value, information benefit, usefulness, pleasure, or gratification. Such experience will ultimately drive the decision on adopting such innovation. Consequently, contextual embedding and its explanations resemble accounts of traditional product diffusion processes, such as how and why telephone use diffuses in a user populations. Like with telephone, the diffusion is conditioned by how performances of the digital material are regulated in each use context, such as recent regulations of tracking software during the COVID-19 pandemic. The diffusion is also is driven by the cost of use and level of effort required to assimilate the innovation. The latter is largely determined by the complexity and versatility of the innovation and the actor's absorptive capacity. On the other hand, the contextual embedding process differs significantly from diffusing industrial products. First, it allows and draws on expansive virtualisation of digital innovation to further innovation. Because of the conventional semantics of the digital material, the diffusion allows constant repurposing of the meaning and uses of the digital material often to unexpected purposes and settings. Scholars call this high interpretive flexibility of digital material (Arvidsson et al., 2014). The success of contextual embedding depends highly on the state of the operational embedding and to what extent and how the digital material performances have been properly contextualised with specific hardware. This may change during the use and consequently change the value of the innovation. For example, ride sharing as a digital innovation became possible only when the whole service could be contextually embedded and performed using powerful enough and common smartphones owned by drivers that could run both the ride-sharing app and a navigation service (complementarity) as part of the service. The former offered a means to make any car a taxi at the moment the driver and the car were connected to the service, and the latter replaced the driver's knowledge of how to drive from point A to point B with a performed digital material (mapping service). This allowed any car owner to connect to a ride-sharing service (Tilson et al., 2021).

Based on the foregoing analysis, digital Innovation regime is generally organised into four phases: (1) discover product or behaviour (ideation); (2) abstract to digital material (virtualise); (3) implement and replicate digital material as performance (variations in operational/contextual embedding); and (4) deliver product and/or behaviour though a performance of digital material. In this sequence, only the first phase is similar to the industrial innovation regime. The innovation starts with a novel idea that takes advantage of some novel features of the physical world or introduces novelty into the social world or individual behaviours. In the next phase, the idea must be virtualised into a model of a digital material specification (data, code) which is then implemented, replicated, and contextualised through ongoing operational and contextual embedding. The implementation and replication phase is deferred or ephemeral in the sense that the actual performance of the product is ultimately determined by the concrete digital material/hardware combination during runtime when the innovation is deployed as performance at the delivery phase of innovation.

Generally, in the digital regime, innovation moves from the idea first to the middle of the sandwich, that is, into addressing the correct digital material representation, and then to forms of carrying out the operational and contextual embedding through implementation and replication. The logic of physical discovery still applies with physical products (hardware) instrumental for implementing and replicating digital material through operational and contextual embedding. But this logic is not a central pathway towards innovation. It is replaced by another (inner) semiotic layer that follows a different logic of discovery of semantic categories and behaviours. The logic of physical discovery, synthesis, and manufacturing and related costs represents a boundary condition of how to replicate and effectively deliver digital material performances. Because of this, the innovation is incomplete – there is always more to virtualise and contextualise – and it can change goals and functions due to high interpretive flexibility and the iterative nature of the innovation. One reason for this is that the three processes largely run on orthogonal paths. The initial operational embedding nearly always differs from how the operational embedding is carried out during the actual delivery. Similarly, the contextual embedding can be varied significantly over time depending on the chosen materialisation and delivery strategy (due to the loosely organised service stack of N-digital layers in Figure 1). The phases and related embedding processes are never sequential, but always interleave and run parallel. Moreover, the feedback loops between the phases are stronger and often immediate. This results in the high fluidity in the innovation scope, activities, participants, and diffusion outcomes (Nambisan et al., 2017). Another unique characteristic is the increased speed of innovation and scaling: it is easier to shape and modify digital representations and change related agreements than to shape physical material and change how to shape it and distribute it. It is also easier to scale (Nambisan et al., 2017). As a result, digital innovation processes advance and change at different rates and speed compared with innovation processes in the industrial innovation regime.

The point of this essay is to identify essential differences in what enables and is conducive for digital versus industrial innovation and how they organise as systems. While writing this piece, I was motivated by the need to increase clarity of the new logic of digital innovation – a topic I initiated with my colleagues in Yoo et al. (2010) that clarified the impact of the N-layer architecture of the digital service stack on innovation. I expand this view to the sandwich model of how the stack relates to innovation environment, and I show that the differences in the logic are centred on differences in leverage points in the system where actors can produce novelty. In the industrial regime, this is circumscribed broadly into the discovery and synthesis and the manufacture and distributed phases. In the digital innovation regime, the points are circumscribed into expansive changes in the operational, virtual, and contextual embedding and their mutually interdependent dynamics, which over time ushers the digital innovation forward. The next step in the analysis will be to expand and map how the material world increasingly melds with digital material. This will enable new types of interactions and performance in material and social environments (such as robotics and autonomous cars). This shift will involve a new round of discovery about how the three processes need to be carried out and can be leveraged to expand digital innovation. The next round of change will cut into pieces the industrial regime from which the new digital innovation regime was borne.

## Notes

1. There are several excellent historic analyses of how such models emerged and were perfected during a period from 1850 to 1970 (see Chandler, 1990; Hughes, 1989).
2. This argument is simplified in purpose somewhat. Industrial innovation in can be also nonlinear in that manufacturing capabilities may already be available from which new innovations emerge, for example, by repurposing some existing capabilities for COVID-19 equipment. Or modular platforms can be in place before ideas come into fruition, as exemplified by investments in traditional technology platforms for automobiles, or in knowledge platforms such as the ones in 3M (Karnøe & Garud, 2012).
3. How such digital technologies were organised in car industry at the height of this period is reported in King and Lyytinen (2004).
4. We call digital representation any string of 0 and 1 that has a shared agreed meaning in any given context. A digital object is a digital representation with clear definition and use purpose in a setting like a payroll record or a CAD/CAM model.
5. Just a change of one bit's value can fundamentally change the meaning of the code.
6. Note that in Figure 1 the direction of the embedding does not match with the direction of the arrows, that is, up or down, but, instead it conveys whether it is the digital (grey) being embedded with physical (white), or vice versa.
7. Both examples have a different and evolving operational and virtual embedding. In the first phase, those cover agreements and digital representations of stocks, prices, money, trades, and so on. In the latter they involve representations of car geometry, hit strength or point, weight, speed, and so on.
8. Recently, this embedding has become a subject of increased virtualisation (called cloud computing), whereby the connection between the digital and hardware has been rendered

dynamic and non-transparent by adding a separate digital layer that coordinates and controls how the digital material hits the hardware in a distributed way during a dynamic embedding of the operations.

9. These presentations follow strictly Ludwig von Wittgenstein's famous last proposition in *Tractactus*: '*Whereof one cannot speak in '0' and '1', thereof one must be silent*.' (Wittgenstein, 1922). In this sense, virtual embedding has a fixity and comes with social inertia related to agreements. But the form and structure of representation can be changed relatively easily as well as what the agreement means (a common trick in repurposing data fields for other uses in many applications).
10. Recently, the device is rather any product because cars, refrigerators, and faucets may share computing capacity.
11. Consider rules and conventions around how we are expected to use mobile phones and related services in different settings in work and family life and at different times of the day.

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